# Development of a pre-verified epd tool with process simulation capabilities for the aggregates industry

*sustainability*

MDPI

*Article*

# Development of a Pre-Verified EPD Tool with Process Simulation Capabilities for the Aggregates Industry

**Panagiota Papadopoulou [1], Diego Peñaloza [2,3], Gauti Asbjörnsson [1,*], Erik Hulthén [1] and Magnus Evertsson [1]**

[1] Department of Industrial and Materials Science, Chalmers University of Technology, 412 96 Gothenburg, Sweden; panpapa@chalmers.se (P.P.); erik.hulthen@chalmers.se (E.H.); magnus.evertsson@chalmers.se (M.E.)
[2] Peab Anläggning AB, 269 73 Förslöv, Sweden; diego.penaloza@peab.se
[3] IVL Swedish Environmental Research Institute, 114 28 Stockholm, Sweden
* Correspondence: gauti@chalmers.se; Tel.: +46-31-772-13-16

**Abstract:** This paper has two aims: to describe the current status and challenges of aggregates producers regarding the analysis and communication of environmental information of their products and to present a layout of a pre-verified tool with simulation capabilities that could assist aggregates producers with their environmental goals. Semi-structured interviews were conducted with three Swedish aggregates producers, an aggregates customer, and an expert agency. Additionally, published Environmental Product Declarations (EPDs) for aggregates and the EN 15804:2012 + A2:2019 were studied to reveal current practices and upcoming changes due to the updated standard. The synergies with process simulations were explored as a step towards using the EPD framework for continuous improvement of aggregates production. The interviews indicated that the main challenge for aggregates producers is the lack of easily available plant data for environmental calculations and clearly defined environmental goals at each plant. The proposed tool uses a common process flowsheet for both EPDs and simulations and has a pre-defined LCA module. The use of such a tool is expected to raise the environmental interest at aggregates plants and improve collaboration with LCA experts. Since the analysis is based on the Swedish aggregates market, the interview results are not directly generalizable to the European context.

**Keywords:** EPD; LCA; pre-verified EPD tool; aggregates; crushing plants; process simulations; Plantsmith

check for updates

**Citation:** Papadopoulou, P.; Peñaloza, D.; Asbjörnsson, G.; Hulthén, E.; Evertsson, M. Development of a Pre-Verified EPD Tool with Process Simulation Capabilities for the Aggregates Industry. *Sustainability* **2021**, *13*, 9492. https://doi.org/10.3390/su13179492

Academic Editor: Jacek Michalak

Received: 25 June 2021
Accepted: 3 August 2021
Published: 24 August 2021



## 1. Introduction

From the main ingredient in concrete and asphalt to a final product for railway tracks, aggregates constitute an indispensable component of industrial societies. The annual demand for aggregates is estimated at 50 billion metric tons globally, making aggregates the largest amongst the non-energy extractive industries in terms of tonnages produced and people employed [1]. The environmental impact of the aggregates during their lifecycle is thus important to be assessed, monitored, and communicated among stakeholders to get a better overview of the industry's environmental impact and identify areas of improvement.

Factors that can influence the gathering and use of environmental impact information include, for example, demands or incentives from external stakeholders such as governmental bodies, or requests from product chain stakeholders such as a company's suppliers or customers that ask for environmental information to inform their purchase choices or to use them for their environmental assessment [2]. In the case of the aggregates industry, the increased demand for environmental data of aggregates products comes from the construction industry and the corresponding governmental agencies [3–5]. The environmental data provided by the aggregates producers need to be transparent, comparable, and representative of the aggregate products under consideration. A Type III Environmental Product Declaration (EPD) according to the rules for the construction products [6] becomes then a useful tool for aggregates producers as it is an industry-accepted document to communicate product-specific environmental impacts [5] while the background Life Cycle Assessment (LCA) report of the EPD can be used for identifying environmental hotspots at a plant level [7].

EPDs are also mentioned in the Construction Products Regulation (CPR) as a tool to assess the environmental impacts of construction products and should be used if available [8]. The CPR aims at increasing the transparency of construction products entering the European market and ensuring that they fulfill some Basic Work Requirements (BWR). The EPDs could be used to assess the BWR 7 that refers to the sustainable use of resources [9]. The assessment of the construction product is documented in the Declaration of Performance (DoP). To increase the reliability of the DoP, an appropriate system of Assessment and Verification of Constancy of Performance (AVCP) is used. The AVCP system defines the measures and actions by the manufacturer and potentially external bodies that lead to the declared DoP.

For the aggregate products within Europe, the overall number of published EPDs remains, however, relatively low among aggregates producers. Forty-two EPDs for aggregate products and one sectorial EPD for the Swiss aggregate production—covering 500 quarries—were found among 30 program operators [10] that publish verified EPDs according to EN 15804:2012 + A1:2013 in a total of approximately 26,000 quarries in Europe [5]. To develop EPDs, different approaches exist which may vary among program operators. For example, companies could use a general-purpose LCA tool, a tool that produces pre-verified EPDs, or have themselves a verified internal process that produces verified EPDs [11–13]. These approaches vary mainly in the verification process needed for the EPD and the flexibility for the EPD developer regarding certain methodological choices, such as choice of LCA data or system boundaries. The option that the company chooses may depend on the number of EPDs that the company aims at producing, the resources within a company, and the existence or not of a pre-verified EPD tool for the specific product category.

A sector-specific pre-verified EPD tool is, therefore, a step towards increasing the number of EPDs developed, assisting both larger and smaller producers in calculating and communicating their environmental impact. Such a tool could potentially be implemented within an AVCP system for aggregate products to cover BWR 7. However, EPDs and the underlying LCAs follow a retrospective approach and black-box modeling of the production which hinder the use of EPDs as a tool for continuous improvement of a crushing plant or when changes need to be evaluated. To assist in a prospective environmental analysis and a more in-depth understanding of the environmental impacts of crushing plants, process simulations can be combined with the pre-verified EPD tool.

This study has two aims: to describe the current status and challenges that the aggregates producers face in Sweden regarding the analysis and communication of environmental information of their products and to provide a layout of a pre-verified EPD tool with simulation capabilities specifically for aggregates producers. The layout of the tool is based on input from aggregates producers, EPD experts, and reviews of EPDs and corresponding standards. The basis for the process simulations is previous research from the Chalmers Rock Processing System (CRPS) group focusing on crushed rock from quarrying and mining. The Swedish aggregates producers that were interviewed produce mainly aggregates for construction. Some of their plants sometimes process rock from tunnel projects or smaller quantities of crushed concrete and asphalt. However, the plants are not specifically designed for recycling and handle those products separately from the main material stream. Other types of products, such as natural stones and manufactured and recycled aggregates, are not currently covered by the tool but are discussed in the paper.

## 2. Current Status

### *2.1. EPDs for Aggregates*

An EPD has as a goal to communicate the potential environmental impact of a product, in this case, the aggregates [7]. The environmental impact is calculated based on the LCA methodology and the respective Product Category Rules (PCRs). PCRs, as defined in ISO 14,025 standard, are additional guidelines on how to calculate the environmental impact of a product within a specific category. PCRs can be developed by different program operators, which can result in misalignments and a lack of comparability among EPDs produced based on PCRs from different program operators [14].

In the construction and building sector, the EN 15,804 standard provides the core rules for the PCR development of the different construction products aiming at counteracting the harmonization issues [15]. As a consequence, PCRs for aggregates that follow the EN 15,804 standard can potentially provide comparable results. Additional initiatives towards harmonization and mutual recognition exist also from program operators [16]. Table 1 describes the 38 valid published EPDs for natural aggregates that follow the EN 15804:2012 + A1:2013 Standard (EPDs for recycled and manufactured aggregates can be found here: [17–21]). Since EN 15804 is limited to the European context, Table 1 covers EPDs in Europe.

**Table 1.** Description of published EPDs for natural aggregates that follow the EN 15804:2012 + A1:2013 standard.

| Program Operator | Publication Year (Quantity) | PCR | Software and Database | No of Companies |
|---|---|---|---|---|
| The International EPD System | 2020 (5) [22–26]<br>2019 (1) [27]<br>2017 (2) [28,29] | PCR 2012:01. Construction products and construction services: v2.33 [22,24], v2.31 [26], v2.3 [23,25,27], v2 [28,29] | GaBi 8: Software and Database (2020 [24], 2019 [22,23,27], 2017 [28,29])<br>SimaPro 8 and Ecoinvent v3.4 [25]<br>SimaPro 9 and Ecoinvent v3 [26] | 4 |
| The Norwegian EPD Foundation | 2021 (8) [30–37]<br>2020 (12) [38–49]<br>2019 (2) [50,51]<br>2018 (3) [52–54]<br>2017 (1) [55] | NPCR Part A: Construction products and services v1.0. April 2017 [30–39,41–48,50–54] + NPCR018 [40,49]<br>CEN standard EN 15804:2012 + A1:2013 [55] | EPD-generator for the Norwegian Aggregates association v1.0 by LCA.no [30–51], LCA.no (2018) EPD generator [53,54]—Both Østfoldforskning's databases (2015–2017) and Ecoinvent v3.3<br>SimaPro 8.2.3.0 and Ecoinvent v3.2 [52]<br>Gabi 2016 and Ecoinvent v3.3 [55] | 11 |
| BRE Global | 2018 (3) [56–58] | BRE Environmental Profiles 2013 [56–58] | BRE LINA and Ecoinvent v3.2 [56–58] | 1 |
| SÜGB | 2018 (1) [59] | PCR Instructions for Stone Construction Materials 1.4.1–1 02.05.2018 | SimaPro 8.5 and Ecoinvent v3.4 | 1 [1] |

[1] This EPD is for the average aggregates produced by members of ASAC—Association of the Swiss Aggregates and Concrete Industry, and it includes both natural and recycled aggregates.

Based on Table 1, only four program operators have published EPDs for natural aggregates for 16 companies and one Association with the number of EPDs being increased from 2020 and onwards. Most of the EPDs refer to specific plants with only four EPDs covering average products from more than one plant [25,52,55,59]. Each program operator is currently using their own PCRs which are compatible with the EN 15804:2012 + A1:2013, and only two of the EPDs have mentioned a complementary PCR (c-PCR) for aggregates [40,49]. Currently, all EPDs for aggregates are cradle-to-gate and they use as declared unit one ton of aggregates. To create these EPDs, four software have been used: two of them are pre-verified EPD tools that are connected to a specific program operator (EPD-generator from LCA.no and BRE LINA that is powered by SimaPro), and the other two are general-purpose LCA software (GaBi and SimaPro) that have available EPD templates. For the LCA data, three different databases have been used in different versions, the Gabi database, the Ecoinvent v3, and Østfoldforskning's databases (2015–2017). As the new EN 15804:2012 + A2:2019 standard came into action in 2019, the currently existing PCRs for aggregates products need to be revised to adapt to the new standard.

### 2.2. Pre-Verified EPD Tools

To facilitate the development of EPDs, the Norwegian EPD Foundation and the International EPD System have included in their General Program Instructions (GPI) different options for pre-verified tools [12,13]. The Norwegian EPD Foundation includes three different types of tools in their GPI: The "Background LCA data tool", the "Reference flow tool", and the "Process certification tool". The first two options have fixed and verified LCA data and EPD-template while the third option does not pose restrictions on the LCA data. The difference between the first two options is that the "Reference flow tool" has a verified and fixed mapping between the reference flow and the LCA data, thus requiring fewer resources to review the produced EPD. According to the GPI of the Norwegian EPD Foundation in the case of the "Reference flow tool": "*The independent reviewer shall have production and process knowledge but may be either an internal or external reviewer to the owner of the tool*". In the case of the "Process certification tool", the third-party verification is performed on the process of creating EPDs and not each EPD. All but one of the EPDs published in the Norwegian EPD Foundation from 2018 and onwards have used a "Reference flow tool" which from 2019 belongs to the Norwegian Aggregates Association.

The International EPD System has a similar arrangement for pre-verified EPD tools and certified EPD processes. For the tool they state in their GPI: "The LCA model used in the tool is parameterized for the bill of potential materials and/or product components in a way which allows the user of the tool, to modify a pre-defined selection of input data or choose from a pre-defined menu of product components connected to a specific product to produce a specific EPD. The LCA model nor the menu can be changed by the user". The EPDs resulting from such tools need to be verified by a third party. In that case, the verification is performed in the input user data. None of the EPDs published in the International EPD system so far have used a pre-verified EPD tool (see Table 1); however, the EPDs of one of the companies are a product of a certified EPD process (see EPDs [22–24,27]). Another EPD-generator which is certified for aggregates products has been developed by One Click LCA [60]. One Click LCA and the International EPD system have announced their collaboration so that EPDs from the first are published directly to the second [61].

Pre-verified tools for other industries and products have been approved by both the Norwegian EPD Foundation and the International EPD System. More specifically, the first has approved 18 tools from companies and associations [62] while the second has approved a tool from the Global Cement and Concrete Association (GCCA) [63].

### 2.3. Process Simulations and LCA

The cradle-to-gate EPDs for aggregates and the underlying LCAs provide a common recipe for calculating and communicating the environmental impact of aggregates products. Since the goal of EPDs is to communicate environmental impact and not to be proactive, they consider production as a black box of input and output material and energy flows. This approach does not allow an evaluation of changes in operations in a proactive way. To provide aggregate producers more benefits from developing an EPD, process simulations can be integrated with LCA software to track the different energy and material flows. Segura-Salazar et al. analyze this integration in different process industries and discuss the efforts within the mining and minerals industry [64].

Minerals processing simulation software that can be used to model crushing plants include JKSimMet [65], METSIM [66], MODSIM [67], USIM PAC [68], IES [69], and HSC Chemistry [70] while dedicated simulation software for crushing plants include Aggflow [71] and the manufacturer-specific PlantDesigner [72] and Bruno [73]. From the mentioned software, HSCSim has a linked LCA module to Gabi and OpenLCA software [74], and USIM PAC can provide the LCI data for an LCA [75]. The approach of combing HSC Sim and LCA software has been described by Reuter et al. [76] and has been demonstrated in many metallurgical application areas [76–80]. The currently available pre-verified EPD tools used for aggregates are not linked with any process simulation tool.

## 3. Methods

The system that surrounds aggregates producers was initially drawn as a tool to identify the different stakeholders and influencing factors in the tool development [81]. Figure 1 provides an overview of this system. The system is divided into internal and external environment of the company: the internal environment is the one that the company has influence over and can be viewed from process, plant, and company level; the external environment is the one that the company cannot control; however, it gets affected by it.

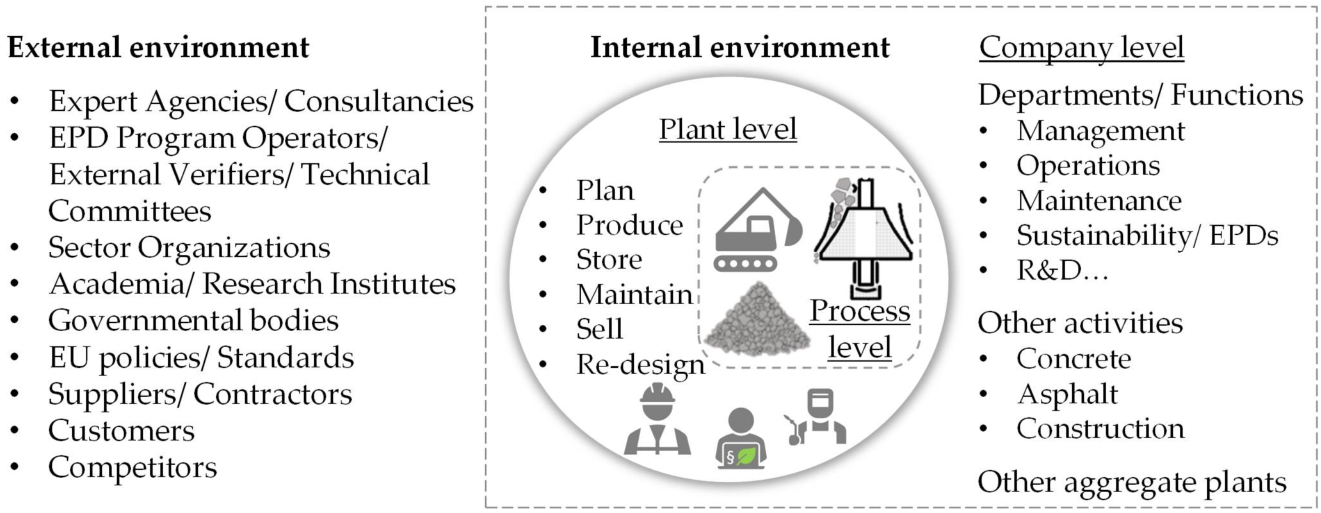


**Figure 1.** System description of aggregates producing companies [81].

The current status and challenges of aggregates producers were analyzed through interviews and focus groups with representatives from three large Swedish aggregates producers in two phases. In phase 1, the company representatives were from the company level while in phase 2 they were from the plant level. In phase 1, in addition to the current status and challenges, stakeholder input was gathered regarding the tool development. This input was both from the companies but also their external environment and more specifically Swedish Transport Administration (STA) and the Geological Survey of Sweden (SGU). STA is one of the main customers of aggregates products in Sweden and already accepts EPDs produced from the EPD tool that exists for concrete production. An interview with a geology expert from SGU was also conducted to explore synergies between the tool and geological components of the plants. Table 2 describes the interviewees' profiles in both phases.

**Table 2.** Description of participants in interviews/focus groups.

| Stakeholder | Phase 1 | Phase 2 |
|---|---|---|
| Company A | LCA specialist | Plant manager |
| Company B | Project leader in Sustainability, LCA specialist [1] | Business manager, plant manager, operator of mobile crushers [1] |
| Company C | Project leader in Sustainability of asphalt, Raw Material, Supply manager [1] | Plant Operator |
| Customer (STA) | Expert within the field of LCA | - |
| Expert agency (SGU) | Geology expert | - |

[1] Denotes focus groups.

All three companies in Table 2 are considered large and have multiple production sites around Sweden. They also produce concrete and asphalt, and aggregates production is one part of their business. Additionally, two of the companies have previously developed at least one EPD for aggregates products, and the third was willing to start the gathering of the necessary data for the EPDs. Small and medium-sized (SME) producers were not directly interviewed at this stage; however, they were considered throughout the process.

Two protocols with open-ended questions were created, one for phase 1 and one for phase 2. In phase 1, an early representation of the tool's layout was used to stimulate the participants during the discussion around the expectations from the tool. All the interviews and focus groups with the companies were recorded. The recordings of phase 1 were combined with notes during the interviews, while the recordings of phase 2 were transcribed and then analyzed. The other two interviews were not recorded but notes were taken. Thematic analysis was used to analyze all the raw data from the interviews and focus groups using the NVIVO 12 software.

Besides the stakeholder input, the 15804:2012 + A2 and the currently published EPDs within the aggregates industry (see Table 1) were also reviewed to develop the layout of the pre-verified EPD tool with the simulation capabilities. The tool is based on the European standard EN 15804:2012 + A2:2019. As a program operator, it was chosen EPD International as they are located in Sweden and have a harmonization agreement with operators around the world. The PCR considered is the PCR for construction products from EPD International, and at a later stage, the PCR from European Aggregates Association (UEPG) will also be reviewed since, currently, it is under development. For the tool verification, the General Program instructions from EPD International are reviewed.

For the simulation capabilities, the platform of Plantsmith is used [82]. Plantsmith is a web-based process simulation software. The simulations are steady-state and include the equipment of a crushing plant. This study covers the upcoming LCA module of Plantsmith and the operation data that are inserted into it. The pre-verified EPDs will be developed within this LCA module. Figure 2 shows a schematic representation of the scope of this paper and how it is connected to previous research within the group.

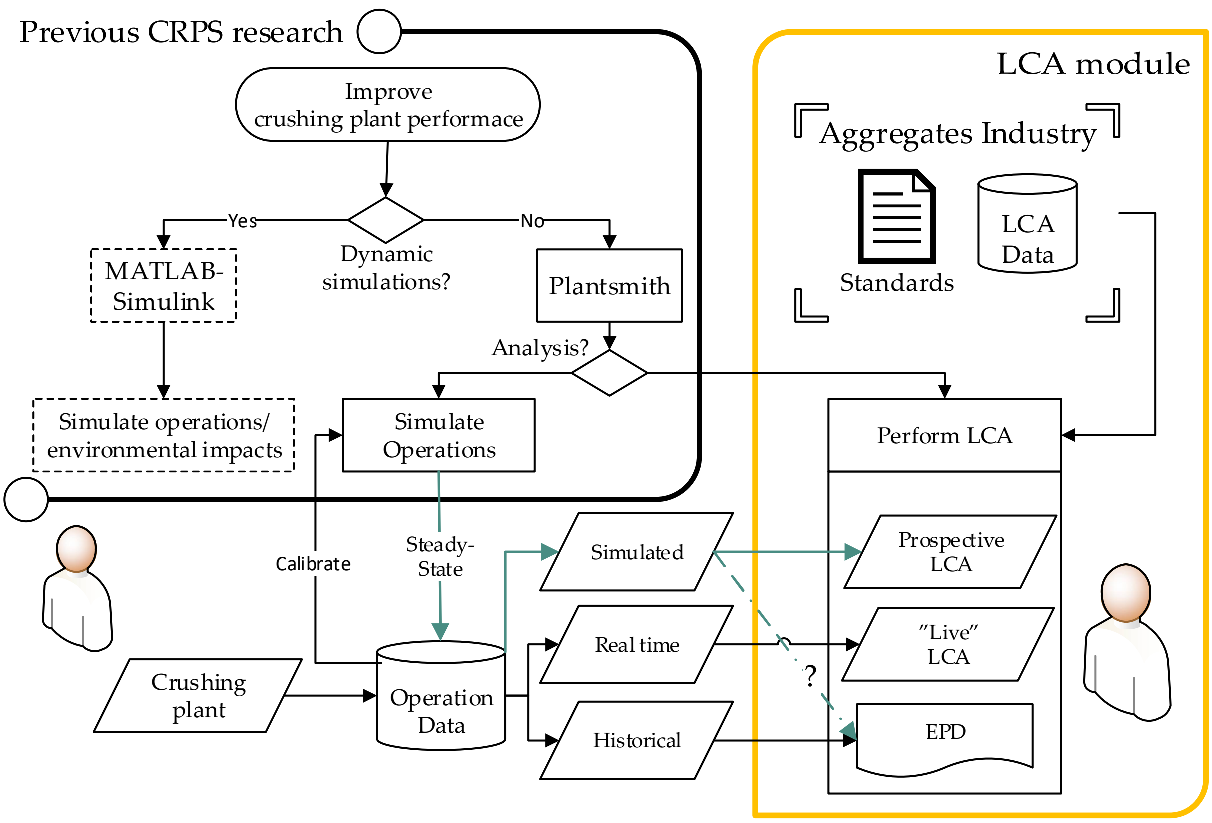


Figure 2. Previous process simulation work and scope of the paper (yellow).

## 4. Results and Discussion

### 4.1. Stakeholder Input

#### 4.1.1. Phase 1

Table 3 provides an overview of the three companies interviewed and the views of their environmental expert(s). All three companies are part of the fossil-free Sweden initiative, which for the construction sector implies 50% reduced greenhouse gas emissions (compared to 2015) in 2030, 75% reduced greenhouse gas emissions in 2040, and net-zero greenhouse gas emissions in 2045 [83] with the Swedish aggregates industry setting up similar goals [84].

**Table 3.** Phase 1—Current environmental goals, status, perceived challenges, and identified needs of aggregates producing companies based on interviews at the company level.

| Aspects | Company A | Company B | Company C |
|---|---|---|---|
| Environmental goals | At company level: $CO_{2eq}$ reduction, climate-neutral 2045<br>At plant level: Create an EPD for each specific plant | At company level: $CO_{2eq}$ reduction, climate-neutral 2045, fulfill STA's demands<br>At plant level: Create plant-specific EPDs—internally | At company level: $CO_{2eq}$ reduction, climate-neutral 2045 (fuels, electrification), fulfill STA's demands<br>At plant level: Measure important environmental aspects, create an EPD |
| Status | EPDs: Certified EPD process, published EPDs for specific plants<br>Data: In the process of digitalizing electricity data<br>Plant level: Improvement actions based on personal initiatives | EPDs: Externally done—for an average plant<br>Plant level: Yearly follow-up of some indicators (e.g., electricity, diesel), use sporadically environmental fact sheets | EPDs: Have not published an EPD for aggregates<br>Plant level: Gather data for every region, type, and amount of material, electricity, diesel (mainly from invoices) |
| Perceived challenges | Data: Finding the data needed for the LCA, plant managers' lack of time to gather the data needed for LCA/EPD<br>Knowledge: Process understanding by the LCA practitioner | Data: Gathering and verifying data from different parts of the organization, measuring parameters for LCA well enough<br>Tools: Lack of digital tools to capture and send process data to the EPD tool<br>Knowledge: Conveying how process changes affect the environmental performance of the plant | Plant managers' limited time and varying interest to engage in environmental impact questions. Quick implementation of board decisions to plant level |
| Identified needs | Data: Digitalization of diesel data, digital infrastructure in each plant | Data: Collect data needed for environmental calculations often, increase follow-up of environmental impacts at both levels | Data: Use of digital tools, collect/measure data needed for environmental calculations (e.g., explosives), use specific LCA data |

The two companies that have not yet created a plant-specific EPD, B and C, have explicitly mentioned as part of their environmental goals to fulfill the environmental requirements from the Swedish Transport Administration (STA). STA demands from its suppliers to reduce the climate impact of the infrastructure project they are involved in, and it additionally provides economic incentives for further reductions [85]. According to the interview with the LCA expert from STA, their suppliers have to use the tool Klimatkalkyl to monitor the climate impact of their project since early stages and planning. As the LCA expert mentioned, Klimatkalkyl includes standard default values for process parameters, and LCA data and the suppliers can update these values with specific, more realistic data during the project. These default generic data in the tool are typically more conservative than specific data (EPDs). Therefore, it is of interest for construction companies to buy from suppliers with published EPDs if they want to obtain the incentives by STA. At the later stages of the project, the results from Klimatkalkyl are used by STA to choose a supplier. As the LCA expert pointed out, Klimatkalkyl provides the contractors with incentives, not detailed steering. Based on STA's tendering system, EPDs can be used to verify the climate performance for both individual materials and building components [85]. As the LCA expert emphasized, reports with EPD format created by a 3rd party verified EPD tool are accepted without being published given that some additional requirements are fulfilled. In their view, environmental calculations can be used for optimization whereas environmental declarations can be used for follow-up and validation.

To create a plant-specific EPD for aggregates products, it is necessary to collect, measure and verify plant-specific data [15]. The plant data in the case of these three companies are requested from the plant manager by the LCA/sustainability expert. Based on the interviews, data collection could become rather resource-intensive since they may be stored within different parts of the organization, in a format that requires a manual input (e.g., paper, pdf), or they may not exist, issues that have been noted before and may be more prominent in SMEs [86,87]. To ease the process of data collection, all of the companies pointed out the need for continuous data collection and not only towards the end of the year. They also highlighted the need for digitalized data that are more accurate to the invoice information that is mainly used today. Sensor data from the plant equipment are also needed to enable environmental monitoring [88] and calibration of the simulation models if EPDs and the background LCAs are going to be a part of continuous plant improvement. However, the companies are in different levels of readiness concerning digital infrastructure for their aggregates' plants, and only one of them has started to gather electricity data from the machines on a cloud solution. When it comes to the diesel data, all of them are using invoices for their environmental metrics.

Regarding plant managers, they have a high workload, and they usually prioritize lower the environmental impact assessment compared to production performance. The lower prioritization could be due to the lack of specific environmental goals to the aggregates department of the companies which would propagate to the different aggregate plants. Additionally, aggregates are usually not the main contributors to the climate impact of construction projects, and therefore, there is less pressure from the whole sector to mitigate. It is noted from the interviews that the initiatives for environmental control and improvements are based on the plant manager's interest, and they are not part of their core tasks. Therefore, plant managers need allocated time for LCI data handling and to provide their insights into potential environmental improvements.

Another challenge that was lifted was the knowledge transfer between the LCA practitioner and the plant manager. The LCA practitioner has a deep knowledge of the environmental aspects but needs guidance when it comes to the process design and material flow. On the other hand, the plant managers know very well the process, but they also need to understand the influence of their decisions on the environmental impact of the plant and what measures they can take. The interviewees portrayed how collaboration between the two roles should look like:

> *"Environmental specialists should be able to ask the questions why the numbers look the way they do, and the site manager should be able through his or her view answer the question. So instead of asking the numbers and collect them, they can start to discuss how they can develop. They cannot understand perhaps the details of the information as the site managers—Company C"*

Based on the same interviews, the expectations from the tool are summarized in Table 4. The overall categories include both technical and user aspects. The technical aspects identified are the different types of analysis within the "LCA module", the way the tool handles and interacts with data, and how the tool is structured to accommodate the different types of users and analysis. For the user aspects, it was perceived that such a tool will potentially increase environmental awareness and competitiveness at the plant level and collaboration between the plant and the company level. However, it may be also met with resistance at the plant level if it is not a clear part of their tasks.

**Table 4.** Phase 1—Expectations from the tool based on interviews at the company level.

| Category | | Description |
|---|---|---|
| Purpose of analysis | Environmental Product Declarations (EPDs) | Calculations: Results compliant with EPD standards, UEPG instructions, same basis for calculations within the sector—increased comparability of results among companies |
| | | Costs: Cost of creating reports/EPDs considered. Initially, it is more about how much it costs rather than how much money it saves |
| | | Templates: For the text needed for the EPD/LCA, easy to include only parts that refer to the specific plant, results—explain why the different material fractions have different environmental impacts, which parts of the lifecycle have the highest impact |
| | Plant Improvements | LCA/EPD: Include what-if scenarios comparison within the tool |
| | | Process: functionality so that plant managers can fine-tune production in terms of volume and cost and then check in the LCA mode how these decisions influence the environmental impact of the process as a side view |
| | Follow-up | Follow-up of long-term targets or as a continuous follow-up during the year (e.g., Track environmental process data monthly and identify anomalies, real-time view) |
| Data | Import/Export | Generally: Aim for digital data, use units that producers use in production/purchases, provide import function for verification documents of reference data, export both LCA/EPD reports |
| | | Process data: Import data directly from databases, Excel, etc., include costs for the different input flows |
| | | LCA data: Multiple datasets available, be able to change pre-set values chosen by the tool developer, use published EPDs as input data, use external LCA data (with additional verification) |
| | Storage | Possibility to store data/documents internally in the tool and not locally |
| | Source | State the data source in the calculations/report (simulated, generic, specific site) |
| | Connectivity | Communicate with software that collects data from the plant to provide a real-time view (process equipment, trucks, and wheel loaders) |
| Tool structure | Access levels | An administrative account with an overview of every plant that they have registered, and then different accesses depending on the person's role |
| | | EPD/LCA mode: access to environmental information—different LCA data, an overview of production data/information to make sure that the data used are correct (used by LCA specialist) |
| | | Simulation mode: access to simulation tool to create their process and compare what happens if they make changes, not so interested in the input of the environmental calculations but can be interested in the environmental results |
| | Simple/ advanced | Simple/advanced version depending on the level of detail of the analysis Simple: average values, advanced: specific equipment |
| Users | Competitiveness | A potentially competitive atmosphere among plant managers to achieve better environmental results |
| | Awareness | If plant managers see the company's environmental goals, they see that they need to take action, and the tool can help them to understand what they can do |
| | Collaboration | Between plant manager and LCA specialist—contribute with their specific knowledge |
| | Resistance | Motivation: People in production are not very interested in using IT tools, they are not going to use the tool easily. Commonly, a person in a more central position is going to use it (for the LCA) Work overload: Plant managers rarely have time to do anything else than production so they won't do anything that takes more time than necessary—if they are going to use the tool it should be rather quick |

In addition to the expectations from the companies, the geologist from SGU pointed out the potential to include in the tool product specifications and test results to strengthen the documentation (CE marking—mineralogy of material, material descriptions, certification documents from hard rock quarries test results from aggregates for asphalt, material delivery, production sites, etc.).

#### 4.1.2. Phase 2

The goal with phase 2 stakeholder input was to describe the current status and challenges of three crushing plants regarding the roles of different people within the plant, the calculation and use of environmental information, the use of process simulations, and how these three aspects can be connected. Table 5 provides an overview of the plants and the interview results.

**Table 5.** Phase 2: Plant-level stakeholder input.

| Aspects | Company A | Company B | Company C |
|---|---|---|---|
| Plant description | Medium-sized stationary plant. Process equipment runs on electricity. There is a control system for the crushers | Medium-sized stationary plant with mobile crusher(s) that are moved to other plants. Process equipment runs on both diesel and electricity | Large-sized stationary plant with mobile crusher(s). Process equipment runs on both diesel and electricity |
| Plant Customers | Mainly company internal—rather constant need | Mainly company external—rather constant need | Mainly company external |
| Roles at plant level | Plant manager overviews multiple plants, operators in/out of the operating room | Plant manager overviews multiple plants, operators in/out of the operating room. Dedicated mobile crusher manager | They have managers for production, maintenance, vehicles, and operators. One of the operators constantly in the operating room |
| Simulations | No exposure | Used by the business manager in 3–5 projects per year. Plant manager—no exposure | Received training but currently not using them. Eager to try again. |
| Environmental Information | EPD for the plant is used for communication purposes—Electricity consumption is checked yearly, no specific target | Calculate yearly an internal environmental indicator based on diesel/electricity consumption, no incentives for improvement | Careful with handling substances that may harm the environment. No goal connected to the environment while in the operating room |

In the medium-sized plants, there is one plant manager that supervises multiple plants while in the large-sized plant there are different managers for the different operation areas. Plant managers mentioned that the production needs are rather constant, and sometimes they need to do fine-tuning for specific product sizes. They said that the role of operators is to run the plant and perform maintenance to prevent a breakdown while maintaining the quality of the aggregate products. The operator in Company C shared the shame view mentioning that his/her goals are to produce similar amounts of products with the other operators, that the material is of good quality, and to avoid a breakdown. Additionally, the operator noted that a large part of the work is troubleshooting production issues together with people on the field and that he/she gets feedback from his supervisor on the lab results of the material. The settings that he/she runs are decided by his/her supervisor and the production manager who have a lot of experience. For mobile crushers, the mobile crusher manager in Company B mentioned that the main indicators they use for performance are the use percentage of machines and the diesel they consume for transportation and operation of the crusher. Since the plant's yearly production is lower than the capacity of the mobile crusher, their goal is to produce as much material as possible in a batch operation and optimize the transportation of the crushers between the plants.

For company B, the plant manager and the operators identify when and what type of investments are needed, and the plant manager communicates the need to the business manager. The business manager's role is to assist plants within the company with investment projects and act as a connector between the plants and the main company and suppliers. The main goal of the investments is to save money and increase the profitability of the plant. The choice of suppliers is based on economic criteria, technical and maybe environmental solutions, and the lead times.

Regarding simulations, they are currently not used at the plant level in none of the plants, and some of the interviewees have not received training. As the plant manager in company B mentioned, they test "in reality" based on their experience. For all the plants, there are some environmental indicators, such as electricity and diesel that are controlled yearly, but there are no specific targets to reach or incentives to improve. According to the business manager in company B, they have a goal to consume less diesel, and there is a trend to electrify the plants; however, there is a lack of technology to become climate neutral in the aggregates' plants.

### *4.2. Published EPDs for Aggregates and EN 15804:2012 + A2:2019*

#### 4.2.1. Review of Published EPDs for Aggregates

All EPDs reviewed (Table 1) follow the EN 15804:2012 + A1:2013 standard and the PCR for construction products of the respective program operator that published them. Two of the EPDs mention an additional PCR specifically for aggregates products [40,49]. All of them were cradle to gate and covered A1–A3 Modules. While studying these EPDs, some uncertainties emerged regarding the choices of the EPD developer. The uncertainties were about choices in product grouping, description of allocation methods, data source of input and output flows, cut-off criteria, assumptions in calculations, and verification options between program operators. These clarifications or level of detail may not be needed by the EN 15804:2012 + A2:2019, but they may improve transparency so the readers could understand better the EPDs, a recommendation also made by Gelowitz and McArthur [89].

Product grouping is present in most of these EPDs for aggregates, and there are a couple of criteria used. The criterion in most of the EPDs is the number of crushing steps that a product goes through. Another criterion used is a less than 10% difference in a specific impact category or if a product includes an additive. However, some of the EPDs do not clarify how they have done the grouping or whether or not the products within each group differ less than 10% in all impact categories.

Allocation is performed in most of the EPDs and is based on mass. However, it is not always mentioned how all the input and output flows are allocated. Additionally, the source of the data is not always stated: if they are used from invoices, measured from sensors in the trucks and equipment, or estimated by someone within the plant. Secondary materials are reported as kilograms in the results section, but it is usually not stated what type of materials they are and how they are allocated. Cut-off criteria and assumptions are not at the same level of detail in all EPDs.

For the verification of the EPDs, the International EPD System and the Norwegian EPD Foundation have different approaches for the use of pre-verified EPD tools. The first one requires external verification of the plant-specific data unless the company has an EPD process in place while the second one does not as long as the aggregates producer has integrated the pre-verified EPD tool within their management system

#### 4.2.2. Changes Due to EN 15804:2012 + A2:2019

The use of the EN 15804:2012 + A2:2019 instead of the previous version of the standard imposes changes that also affect the aggregates products. One of the main changes is the requirement to declare modules C1–C4 and module D unless the exemption criteria described in the standard are fulfilled. For aggregates products, the criteria are interpreted as follows: integration of the aggregate material with other products, no separation or identification of the aggregate material at the end of life, and no biogenic carbon within the aggregates products. For the aggregate products, the new standard implies that there will be two different categories of aggregates: those for concrete and asphalt that fulfill the requirements for exemption of the additional modules and aggregates for structural unbound materials, railway ballast and armor stone that do not fulfill the requirements and need modules C and D. Another change from the updated standard is the allocation method, as economic allocation based on economic value must be applied if the difference in revenue among the co-products is significant. Finally, the number of impact indicators increased from seven to 13 core indicators plus six additional. What is more, most of the indicators that remain from the previous version use different models, so their results are not directly comparable. This change influences the use of the EPDs from aggregates as input data to EPDs for concrete and asphalt during the transition period between the new and old standards.

### 4.3. Synergies with Process Simulations

The goal of the LCA module in Plantsmith is to provide three different types of environmental reports or results: The prospective LCA, the "live" LCA, and the EPD (see Figure 2). The prospective LCA for aggregates plants evaluates changes in the production or designs of new plants. Changes in production include evaluating existing equipment in different settings or plant layouts and evaluating new equipment before buying it. In prospective LCA, process simulations provide representative lifecycle inventory (LCI) data for a state of the process that currently does not exist.

The "live" LCA will use data from the sensors in the equipment and trucks in the plant to calculate the environmental impact in real-time. "Live" LCA would enable people at the plant level to take action once the environmental metrics show an undesired change. Process data from "live" LCA could also be used to calibrate the models for the prospective LCA of an existing plant. The implementation of "live" LCA prerequisites the existence of data acquisition systems at the plant level. If such systems do not exist, calibration could be performed based on experimental data within the plant [90].

For the EPD, one-year historical plant data are needed to create a plant-specific EPD. If there are not power draw sensors in each piece of equipment, it is possible to use process simulations to estimate the power draw at each crushing stage of the plant. For the follow-up of EPDs, "live LCA" could assist in identifying issues when they occur, and the prospective LCA could assist in optimizing the process and evaluating new investments compared to the EPD. All three types of LCA in the LCA module use the same system boundaries, allocation rules, and LCA database to enable comparisons and insights from the results.

### 4.4. Tool Layout

Figure 3 depicts the lifecycle stages and modules to be declared in the EPD for aggregates based on EN 15804:2012 + A2:2019 with the two categories of aggregates (see Section 4.2.2). Aggregates for concrete and asphalt declare A1-A3 modules, and their EPD is used as input to the EPDs for concrete and asphalt. The transportation of crushed concrete and crushed asphalt to the aggregates plant is considered in the EPDs for concrete and asphalt as the C2 module and therefore not counted in the EPD for aggregates. However, the internal transportation of the material is still considered in the EPD for aggregates. Another input to the crushing plant is tunnel rock and clean material masses from construction projects (Figure 3). This material is used on the spot at the construction site or transported to nearby crushing plants, recycling facilities, or temporary storage places. When transported to crushing plants, transportation needs to be considered in the A2 module of the EPD for aggregates, and the material is reported as secondary material.

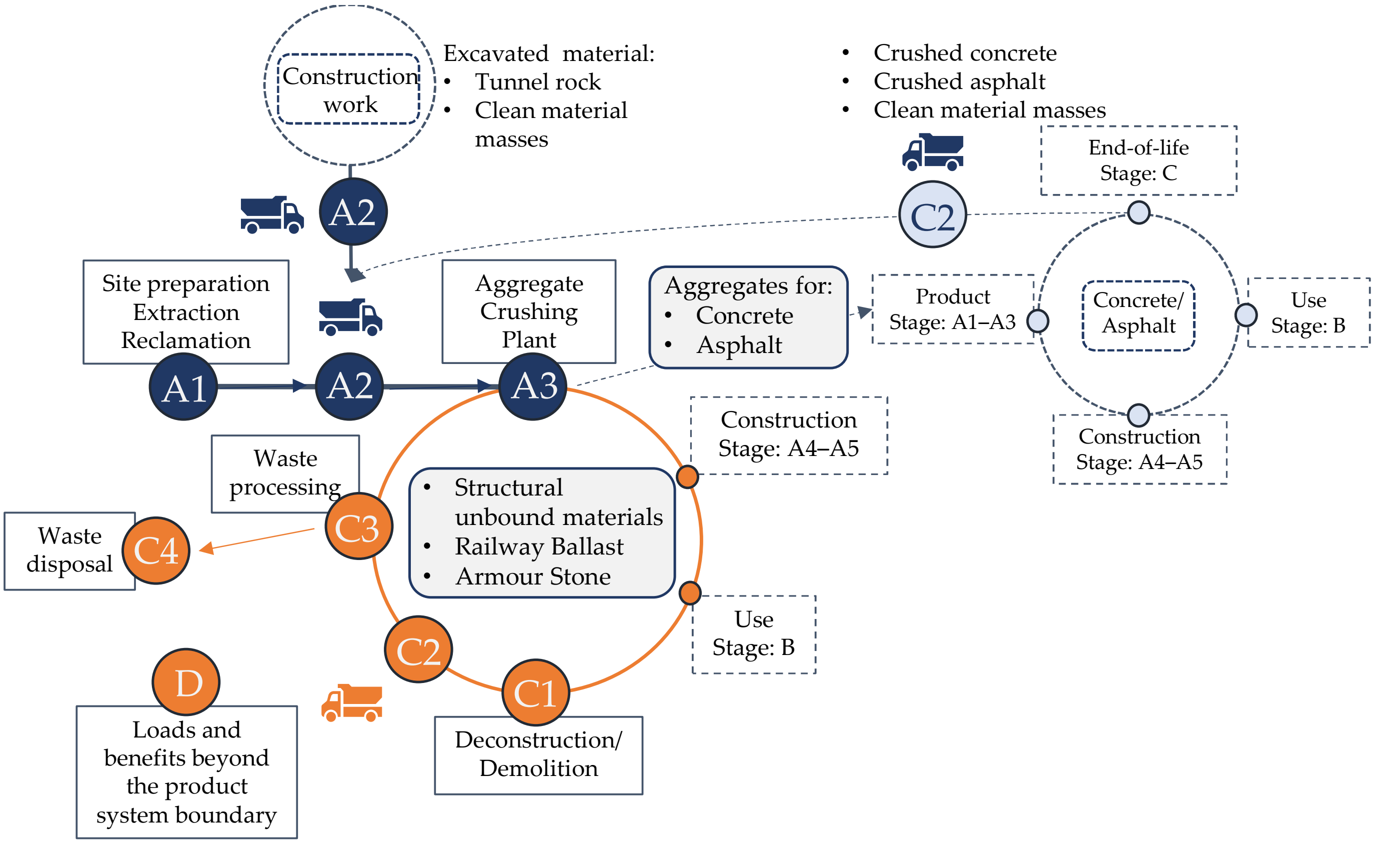


**Figure 3.** Lifecycle stages and modules for aggregates products based on the EN 15804:2012 + A2:2019. Dashed boxes are excluded from the EPDs for aggregates.

Figure 4 depicts the layout of the suggested tool as a process model. The tool receives process data and information as input and provides the different types of environmental calculations as output. The output from the EPD functionality within the tool is a pre-verified EPD and its background report. If this EPD is verified according to the program operator's instructions, it will be uploaded to the operator's EPD portal as machine-readable EPD (in this case the International EPD System) [13]. Some organizations may accept under conditions unpublished pre-verified EPDs from the third-party verified tools as in the case of STA in Sweden. From the "live" and prospective LCA functionality, the user receives environmental and process key performance indicators for their aggregates plant, such as the ones described by Bhadani et al. [91].

The different users of the tool and the choices they make while using the tool are considered uncontrolled factors. To reduce the impact of user choices in the output of the tool, the controlled factors are introduced. Control factors are how the calculations are performed, the LCA data that the tool has access to, the templates that are used for the LCA and EPD report, and the simulation models within the tool.

The calculations are based on the EN 15804:2012 + A2:2019 standard and will be adjusted to follow the upcoming PCR for aggregates by the UEPG. One main parameter is the energy allocation method which is based on mass and different products' paths [81]. The chosen LCA data are specific for different geographical locations and cover the different flows identified in the current LCI for aggregates products. The templates have a high level of detail so that the transparency of EPDs increases and similar information is reported to ease the comparison between the EPDs. For the pre-verified EPD tool, these three modules are verified by a third-party verifier, external to the tool owner, and cannot be changed by the user. Therefore, for an EPD, the verifier has to check the input to the tool and the process data and information and not the whole process.

For the simulation models, the ones that may be used in electricity allocation need also to be verified together with the process of using them. For prospective LCA, there are different unverified simulation models which are chosen based on the available data from the plant, the type of the analysis, and the experience of the user with the process.

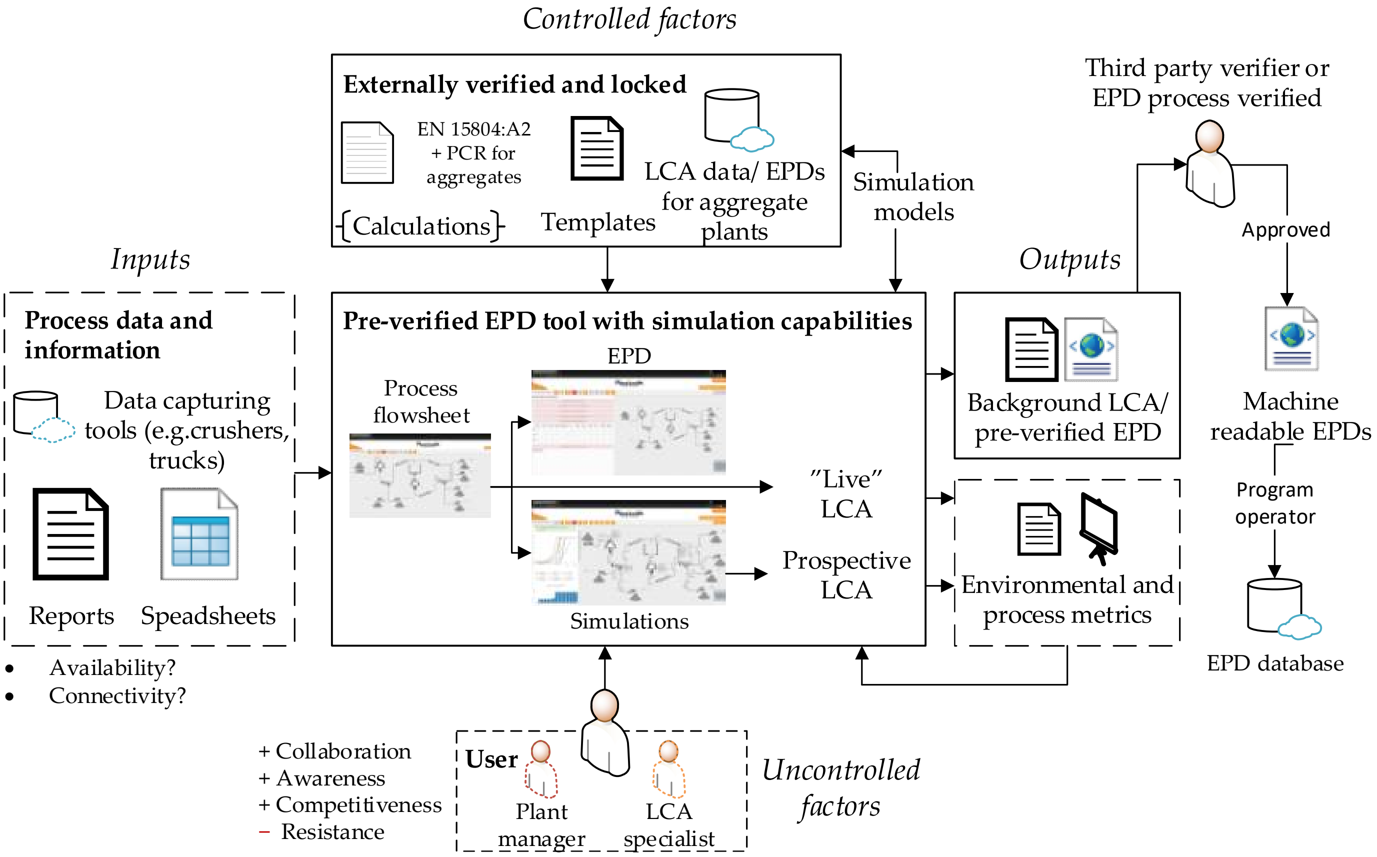


**Figure 4.** Tool layout based on stakeholder input, EPD review, and previous research within the CRPS group.

## 5. Conclusions

This paper explored the current status and challenges that the aggregates producers face while creating environmental data for their plants. Additionally, a pre-verified EPD tool with simulation capabilities was presented to ease the process of creating an EPD for aggregates products and enable continuous improvement of production and proactive engagement of the plant managers. Both stakeholder input and public documentation were used to inform the conclusions. However, the stakeholder input was limited to a relatively small number of actors within the Swedish aggregates industry. Therefore, even though similar challenges may be expected in other aggregates plants within Europe, a more rigorous exploration is needed to understand differences in individual countries, especially at the plant-level points. The main conclusions in the different categories are as follows:

Current Status:

- A relatively low number of EPDs for aggregates products is published considering the number of quarries within Europe.
- All published EPDs for aggregates products follow the previous EN 15804:2012 + A1:2013 standard. This may hinder their use as input data in EPDs that use the updated standard, for example in EPDs for concrete and asphalt.
- The use of a pre-verified EPD tool owned by the Norwegian Aggregates Association seems to increase the number of EPDs published within the country.

- A verified EPD process (as defined by EPD international) seems to increase the number of published EPDs within a company.
- At the plant level, environmental initiatives are usually based on the plant manager's interest.
- Not all companies have a dedicated LCA specialist.

Current Challenges:

- Potential lack of understanding within the plant of what data need to be measured and collected. Company external help needed, potential lack of process knowledge.
- Plant data needed for the EPD not concentrated in one location.
- Lack of sensor data for continuous monitoring of plant equipment.
- Low engagement of plant-level personnel in environmental questions.
- An unclear connection between company-level environmental goals and plant-level operations.
- Limited use of process simulations, no use from the interviewed plant level personnel.
- Wide range of variability among the aggregate products and their properties. The EPD user/reader is responsible to understand how and when to use specific EPDs.
- The absence of a European PCR for aggregates may be a problem for comparability.
- Different GPI among program operators for pre-verified EPD tools and the verification of the EPDs produced by such tools. Need for harmonization at the European level.
- Upcoming PCR for aggregates: Need to harmonize the declared unit, the technical information of the product in connection to the declared unit, and in general the information that should be reported in the EPD.

Tool Layout:

- Developed based on stakeholder input, standards review, and previous research within the CRPS group.
- For EPDs, all LCA calculations are predefined, and the user chooses through available options. Therefore, only input data need to be company externally verified.
- Include a database with sector-specific generic data to ease comparability between EPDs.
- Uses a common process flowsheet for all types of analysis to ease the transition between the analysis modes.
- The integration of simulations provides a proactive way of handling environmental impacts in an aggregates plant.
- Perceived potential to increase collaboration between plant managers and LCA specialists and knowledge exchange.
- To avoid potential resistance at the plant level in using the tool and collecting the data: Need for allocated time to avoid work overload, clear instructions and training, clear plant level goals connected to the use of the tool.

A similar development process could be used to create such tools for different industries. Upcoming research steps include user testing of the tool and inclusion of all aggregate products.

**Author Contributions:** Conceptualization, P.P., G.A., E.H.; methodology, P.P.; validation, P.P., D.P., G.A., E.H., M.E.; formal analysis, P.P.; investigation, P.P.; data curation, P.P.; writing—original draft preparation, P.P.; writing—review and editing, P.P., D.P., G.A., E.H., M.E.; visualization, P.P.; supervision, G.A., E.H.; project administration, E.H.; funding acquisition, G.A., E.H., P.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study has been performed under the project EPD-Berg—"Web-based EPD tool for lifecycle perspective for aggregates production" and supported financially by VINNOVA grant number 2019-00857 and SBUF (Svenska Byggbranschens Utvecklingsfond) grant number 13738.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the privacy of the interviewees.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## References

1. GAIN Global Aggregates Information Network: World Map. Available online: https://www.gain.ie/ (accessed on 19 May 2021).
2. Erlandsson, J.; Tillman, A.-M. Analysing influencing factors of corporate environmental information collection, management and communication. *J. Clean. Prod.* **2009**, *17*, 800–810. [CrossRef]
3. Kylili, A.; Fokaides, P.A. Policy trends for the sustainability assessment of construction materials: A review. *Sustain. Cities Soc.* **2017**, *35*, 280–288. [CrossRef]
4. Toniolo, S.; Mazzi, A.; Simonetto, M.; Zuliani, F.; Scipioni, A. Mapping diffusion of Environmental Product Declarations released by European program operators. *Sustain. Prod. Consum.* **2019**, *17*, 85–94. [CrossRef]
5. UEPG. *European Aggregates Association Annual Review—A Sustainable Industry for A Sustainable Europe*; UEPG: Brussels, Belgium, 2020.
6. CEN. *EN 15804:2012 + A2:2019—Sustainability of Construction Works—Environmental Product Declarations—Core rules for the Product Category of Construction Products*; CEN: Brussels, Belgium, 2019.
7. ISO. *ISO 14025 Environmental Labelling and Declarations—Type III Environmental Declarations–Principles and Procedures*; ISO: Geneva, Switzerland, 2006.
8. Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 Laying Down Harmonised Conditions for the Marketing of Construction Products and Repealing Council Directive 89/106/EEC Text with EEA Relevance. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011R0305&from=EN (accessed on 30 July 2021).
9. Wall, S. CE Marking of Construction Products—Evolution of the European Approach to Harmonisation of Construction Products in the Light of Environmental Sustainability Aspects. *Sustainability* **2021**, *13*, 6396. [CrossRef]
10. Construction LCA's 2021: Guide to Environmental Product Declarations. Available online: https://bit.ly/2021-EPD (accessed on 19 May 2021).
11. The International EPD System: LCA and EPD Tools. Available online: https://www.environdec.com/all-about-epds/lca-and-epd-tools (accessed on 19 May 2021).
12. EPD Norway. *General Programme Instructions for the Norwegian EPD Foundation (v4)*; EPD Norway: Oslo, Norway, 2019.
13. EPD International. *General Programme Instructions for the International EPD® System. Version 4.0*; EPD International: Stockholm, Sweden, 2021.
14. Ingwersen, W.W.; Stevenson, M.J. Can we compare the environmental performance of this product to that one? An update on the development of product category rules and future challenges toward alignment. *J. Clean. Prod.* **2012**, *24*, 102–108. [CrossRef]
15. CEN. *EN 15804:2012 + A1:2013—Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products*; CEN: Brussels, Belgium, 2013.
16. The International EPD System The PCR Partnership Programme. Available online: https://www.environdec.com/global-network/intl-cooperation-ppp (accessed on 4 June 2021).
17. IMS Site Services Limited t/a Greenstone Recycling. *Environmental Product Declaration for Recycled Aggregates*; Irish Green Building Council: Dublin, Ireland, 2020.
18. Repurpose It. *Environmental Product Declaration for Recovered Mineral Aggregates*; EPD Australasia: Nelson, New Zealand, 2020.
19. Officina dell'Ambiente S.p.A. *Environmental Product Declaration for Secondary Raw Materials or Aggregates of Industrial Origin, AG Matrix*; EPD International: Stockholm, Sweden, 2019.
20. Officina dell'Ambiente S.p.A. *Environmental Product Declaration for Secondary Raw Materials or Aggregates Ofindustrial Origin, Sand Matrix*; EPD International: Stockholm, Sweden, 2019.
21. Feralpi Siderurgica Spa. *Environmental Product Declaration for Greenstone Recycled Construction Aggregate*; EPD International: Stockholm, Sweden, 2019.
22. NCC Industry Nordic AB. *Environmental Product Declaration for Aggregates from Uusimaaquarry, Pornainen*; EPD International: Stockholm, Sweden, 2020.
23. NCC Industry Nordic AB. *Environmental Product Declaration for Aggregates from Mäntsälä Quarry Ohkola*; EPD International: Stockholm, Sweden, 2020.
24. NCC Industry Nordic AB. *Environmental Product Declaration for Aggregates from Copenhagen Terminal for Marine Aggregates Avedøre*; EPD International: Stockholm, Sweden, 2020.
25. Holcim. *Environmental Product Declaration for Average Aggregate of Holcim Romania*; EPD International: Stockholm, Sweden, 2020.
26. LKAB. *Environmental Product Declaration for Heavy Aggregates from Kiruna*; EPD International: Stockholm, Sweden, 2020.
27. NCC Industry Nordic AB. *Environmental Product Declaration for Aggregates from Uddevalla Quarry Glimmingen*; EPD International: Stockholm, Sweden, 2019.

28. NCC Industry Nordic AB. *Environmental Product Declaration for Aggregates from the Mobile Crushing Plant in Bjurholm*; EPD International: Stockholm, Sweden, 2017.
29. NCC Industry Nordic AB. *Environmental Product Declaration for Aggregates from the Stationary Crushing Plant Ramnaslätt*; EPD International: Stockholm, Sweden, 2017.
30. Franzefoss Pukk AS. *Environmental Product Declaration for Crushed Stone (Knust Stein/Pukk) Franzefoss avd. Lierskogen*; EPD Norway: Oslo, Norway, 2021.
31. Franzefoss Pukk AS. *Environmental Product Declaration for Crushed Stone (Knust Stein/Pukk) Franzefoss avd. Vassfjell*; EPD Norway: Oslo, Norway, 2021.
32. Franzefoss Pukk AS. *Environmental Product Declaration for Crushed Stone (Knust Stein/Pukk) Franzefoss avd. Steinskogen*; EPD Norway: Oslo, Norway, 2021.
33. Ramlo Sandtak AS. *Environmental Product Declaration for Crushed Stone and Aggregate (Pukk og Tilslag)*; EPD Norway: Oslo, Norway, 2021.
34. Gunnar Holth Grusforretning AS. *Environmental Product Declaration for Natural Gravel and Sand Produced at Laugslet (Naturgrus og Sand Produsert Ved Avd Laugslet, Indre Østfold)*; EPD Norway: Oslo, Norway, 2021.
35. DC Eikefet Aggregates AS. *Environmental Product Declaration for Crushed Stones and Aggregates Produced at DC Seljestokken Aggregates AS*; EPD Norway: Oslo, Norway, 2021.
36. Hamar Pukk og Grus AS. *Environmental Product Declaration for Crushed Stone Produced by Sørli Massetak, Stange (Pukk, Produsert ved Sørli Massetak, Stange)*; EPD Norway: Oslo, Norway, 2021.
37. Gunnar Holth Grusforretning AS. *Environmental Product Declaration for Natural Aggregates Produced by Grasmo Eidskog (Naturgrus, Produsert Ved Avd Grasmo, Eidskog)*; EPD Norway: Oslo, Norway, 2021.
38. Gunnar Holth Grusforretning AS. *Environmental Product Declaration for Natural Gravel, Produced in Hagen (Naturgrus, Produsert Ved Avd Hagen—Vesterhaug, Elverum)*; EPD Norway: Oslo, Norway, 2020.
39. Gunnar Holth Grusforretning AS. *Environmental Product Declaration for Crushed Stone Produced in Gullkista (Pukk, Produsert Ved Avd Gullkista, Sortland)*; EPD Norway: Oslo, Norway, 2020.
40. NCC Industry AS Stone Materials. *Environmental Product Declaration for Crushed Stone Produced in Tjølling Crushing Plant (Pukk, Produsert Ved Tjølling Pukkverk)*; EPD Norway: Oslo, Norway, 2020.
41. NCC Industry AS Stone Materials. *Environmental Product Declaration for NCC Gjølme Crushing Plant (Pukkverk)*; EPD Norway: Oslo, Norway, 2020.
42. Gunnar Holth Grusforretning AS. *Environmental Product Declaration for Crushed Stone Produced in Granerud (Pukk, Produsert Ved Avd Granerud, Nord-Odal)*; EPD Norway: Oslo, Norway, 2020.
43. Rudshøgda Pukkverk AS. *Environmental Product Declaration for Crushed Stone Produced in Rudshøgda Crushing Plant (Pukk, Produsert Ved Rudshøgda Pukkverk, Ringsaker)*; EPD Norway: Oslo, Norway, 2020.
44. NorStone AS. *Environmental Product Declaration for Crushed Rock Produced in Svingen (Knust Fjell Produsert Ved Svingen, Halden)*; EPD Norway: Oslo, Norway, 2020.
45. Feiring Bruk AS. *Environmental Product Declaration for Natural Gravel and Sand, Produced by Grefsrud AS (Naturgrus Og Sand, Produsert Ved Grefsrud AS, Jessheim)*; EPD Norway: Oslo, Norway, 2020.
46. Franzefoss Pukk AS. *Environmental Product Declaration for Crushed Stone (Knust Stein/Pukk) Franzefoss Avd. Lia*; EPD Norway: Oslo, Norway, 2020.
47. NCC Industry AS Stone Materials. *Environmental Product Declaration for Sand Produced in Helle Quarry (Sand, Produsert ved Helle Sandtak)*; EPD Norway: Oslo, Norway, 2020.
48. NCC Industry AS Stone Materials. *Environmental Product Declaration for Crushed Stone Produced in Arna Stone Crushing Plant (Pukk, Produsert ved Arna Steinknuseverk)*; EPD Norway: Oslo, Norway, 2020.
49. NCC Industry AS Stone Materials. *Environmental Product Declaration for Crushed Stone Produced in Hedrum Crushing Plant (Pukk, Produsert ved Hedrum Pukkverk)*; EPD Norway: Oslo, Norway, 2020.
50. Velde Pukk AS. *Environmental Product Declaration for Crushed Stone, Aggregate and Environmental Mass from Velde Pukk AS (Pukk, Tilslag og Miljømasse fra Velde Pukk AS)*; EPD Norway: Oslo, Norway, 2019.
51. Gunnar Holth Grusforretning AS. *Environmental Product Declaration for Crushed Stone Produced in Folbergåsen (Pukk, Produsert ved Folbergåsen, Nes)*; EPD Norway: Oslo, Norway, 2019.
52. Franzefoss Pukk AS. *Environmental Product Declaration for Crushed Stone Construction Aggregate Products, Oslo and Bærum*; EPD Norway: Oslo, Norway, 2018.
53. Feiring Bruk AS. *Environmental Product Declaration for Crushed Stone Produced in Bjønndalen (Pukk, Produsert ved Bjønndalen Bruk AS, Nittedal)*; EPD Norway: Oslo, Norway, 2018.
54. Feiring Bruk AS. *Environmental Product Declaration for Crushed Stone Produced in Lørenskog (Pukk, Produsert ved Feiring Bruk AS, avd. Lørenskog)*; EPD Norway: Oslo, Norway, 2018.
55. Skanska Industrial Solutions AB. *Environmental Product Declaration for Crushed Rock Products (Bergkrossprodukter)*; EPD Norway: Oslo, Norway, 2017.
56. Aggregate Industries UK Limited. *Environmental Product Declaration for Granite Aggregate, Glensanda*; BRE Global: Watford, UK, 2018.

57. Aggregate Industries UK Limited. *Environmental Product Declaration for Granite Aggregate, Bardon Hill*; BRE Global: Watford, UK, 2018.
58. Aggregate Industries UK Limited. *Environmental Product Declaration for Limestone Aggregate*; BRE Global: Watford, UK, 2018.
59. Association of the Swiss Aggregate and Concrete Industry (ASAC). *Average EPD for Aggregates*; Association of the Swiss Aggregate and Concrete Industry (ASAC): Bern, Switzerland, 2018.
60. Bionova Ltd. *One Click LCA*; Bionova Ltd.: Helsinki, Finland, 2021.
61. The International EPD System Announces Partnership with One Click LCA. Available online: https://www.environdec.com/news/the-international-epd-system-announces-partnership-with-one-click-lca (accessed on 19 May 2021).
62. The Norwegian EPD Foundation Approved EPD Tools. Available online: https://www.epd-norge.no/getfile.php/1317847-1616600450/Dokumenter/oversiktepd-verkt\T1\oyper190321.pdf (accessed on 19 May 2021).
63. Global Cement and Concrete Association. *GCCA Environmental Product Declaration Tool*; Global Cement and Concrete Association: London, UK, 2021.
64. Segura-Salazar, J.; Lima, F.M.; Tavares, L.M. Life Cycle Assessment in the minerals industry: Current practice, harmonization efforts, and potential improvement through the integration with process simulation. *J. Clean. Prod.* **2019**, *232*, 174–192. [CrossRef]
65. JKTech Pty Ltd. *JKSimMet*; JKTech Pty Ltd.: Brisbane, Australia, 2020.
66. METSIM International LCC. *METSIM*; METSIM International LCC: Churubusco, IN, USA, 2021.
67. Mineral Technologies Inc. *MODSIM*; Mineral Technologies Inc: Salt Lake City, UT, USA, 2010.
68. Caspeo. *USIM PAC*; Caspeo: Orléans, France, 2021.
69. CRC ORE. *Integrated Extraction Simulator (IES)*; CRC ORE: Brisbane, Australia, 2019.
70. Metso Outotec Oyj. *HSC Chemistry*; Metso Outotec Oyj: Helsinki, Finland, 2021.
71. BedRock Software Inc. *Aggflow*; Bedrock Software Inc: Beaverton, OR, USA, 2021.
72. Sandvik Mining and Construction Sverige AB. *PlantDesigner*; Sandvik Mining and Construction Sverige AB: Svedala, Sweden, 2021.
73. Metso:Outotec Q&A: Bruno Simulation Software for Optimizing Aggregate Production. Available online: https://www.mogroup.com/insights/blog/aggregates/bruno-simulation-software-explained/ (accessed on 19 May 2021).
74. Reuter, M.; Peltomäki, M.; Horn, S.; Nuppumäki, E.; HSCSim LCA. Available online: https://www.outotec.com/globalassets/products/digital-solutions/hsc/49-Sim-LCA.pdf (accessed on 19 May 2021).
75. Bodin, J.; Beylot, A.; Villeneuve, J.; Bru, K.; Chanoine, A.; Duvernois, P.-A.; Françoise, B. Coupling Simulation of Mineral Processing with Life Cycle Assessment to Assess the Environmental Impacts of Copper Production. In Proceedings of the Life Cycle Management Conference, LCM 2017, Luxembourg, 3–6 September 2017.
76. Reuter, M.A.; van Schaik, A.; Gediga, J. Simulation-based design for resource efficiency of metal production and recycling systems: Cases—copper production and recycling, e-waste (LED lamps) and nickel pig iron. *Int. J. Life Cycle Assess.* **2015**, *20*, 671–693. [CrossRef]
77. Abadías Llamas, A.; Valero Delgado, A.; Valero Capilla, A.; Torres Cuadra, C.; Hultgren, M.; Peltomäki, M.; Roine, A.; Stelter, M.; Reuter, M.A. Simulation-based exergy, thermo-economic and environmental footprint analysis of primary copper production. *Miner. Eng.* **2019**, *131*, 51–65. [CrossRef]
78. Elomaa, H.; Rintala, L.; Aromaa, J.; Lundström, M. Process simulation based life cycle assessment of cyanide-free refractory gold concentrate processing—Case study: Cupric chloride leaching. *Miner. Eng.* **2020**, *157*, 106559. [CrossRef]
79. Ghodrat, M.; Rhamdhani, M.A.; Brooks, G.; Rashidi, M.; Samali, B. A thermodynamic-based life cycle assessment of precious metal recycling out of waste printed circuit board through secondary copper smelting. *Environ. Dev.* **2017**, *24*, 36–49. [CrossRef]
80. Hannula, J.; Godinho, J.R.A.; Llamas, A.A.; Luukkanen, S.; Reuter, M.A. Simulation-Based Exergy and LCA Analysis of Aluminum Recycling: Linking Predictive Physical Separation and Re-melting Process Models with Specific Alloy Production. *J. Sustain. Metall.* **2020**, *6*, 174–189. [CrossRef]
81. Papadopoulou, P.; Asbjörnsson, G.; Hulthén, E.; Evertsson, C.M. Utilization of environmental impact simulations in crushing plant operation. In Proceedings of the IMPC 2020: XXX International Mineral Processing Congress, Cape Town, South Africa, 18–22 April 2021.
82. Roctim AB. *Plantsmith*; Roctim AB: Gothenburg, Sweden, 2021.
83. Fossilfritt Sverige. *Roadmap for Fossil-Free Competitiveness: Summaries 2018–2020 (Färdplan för Fossilfri Konkurrens Kraft: Sammanfattningar 2018–2020)*; Fossilfritt Sverige: Stockholm, Sweden, 18–22 October 2020.
84. SBMI. *Swedish Aggregates Association Roadmap for Fossil-Free Competitiveness: The Aggregates Industry (Färdplan för Fossilfri Konkurrenskraft: Bergmaterialindustrin)*; SBMI: Stockholm, Sweden, 2019.
85. STA. Swedish Transport Administration: Climate requirements (Klimatkrav). Available online: https://www.trafikverket.se/for-dig-i-branschen/miljo---for-dig-i-branschen/energi-och-klimat/klimatkrav/ (accessed on 19 May 2021).
86. Strömberg, L. Conceptual Framework for Calculation of Climate Performance with Pre-verified LCA-Tools. *J. Civ. Eng. Archit.* **2017**, *11*, 29–37. [CrossRef]
87. Rocha, M.S.R.; Caldeira-Pires, A. Environmental product declaration promotion in Brazil: SWOT analysis and strategies. *J. Clean. Prod.* **2019**, *235*, 1061–1072. [CrossRef]
88. Bhadani, K.; Asbjörnsson, G.; Hulthén, E.; Hofling, K.; Evertsson, M. Application of Optimization Method for Calibration and Maintenance of Power-Based Belt Scale. *Minerals* **2021**, *11*, 412. [CrossRef]

89. Gelowitz, M.D.C.; McArthur, J.J. Comparison of type III environmental product declarations for construction products: Material sourcing and harmonization evaluation. *J. Clean. Prod.* **2017**, *157*, 125–133. [CrossRef]
90. Bhadani, K.; Asbjörnsson, G.; Bepswa, P.; Mainza, A.; Andrew, E.; Philipo, J.; Zulu, N.; Anyimadu, A.; Hulthén, E.; Evertsson, C.M. Experimental and Simulation-Driven Improvements for Coarse Comminution Circuit Using Plantsmith Process Simulator—A Case Study of Geita Gold Mine, Tanzania. In Proceedings of the Conference in Minerals Engineering (Konferens i Mineralteknik), Luleå, Sweden, 2 February 2021.
91. Bhadani, K.; Asbjörnsson, G.; Hulthén, E.; Evertsson, M. Development and implementation of key performance indicators for aggregate production using dynamic simulation. *Miner. Eng.* **2020**, *145*, 106065. [CrossRef]